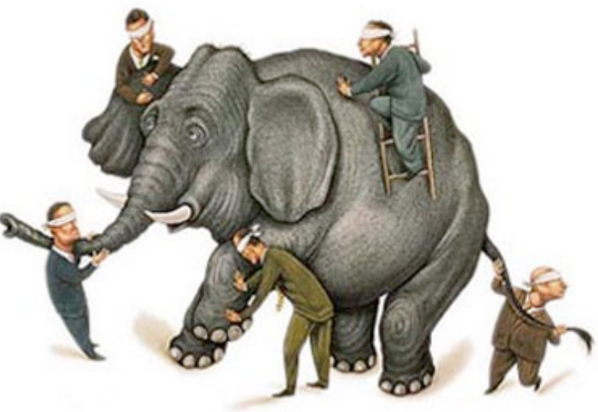
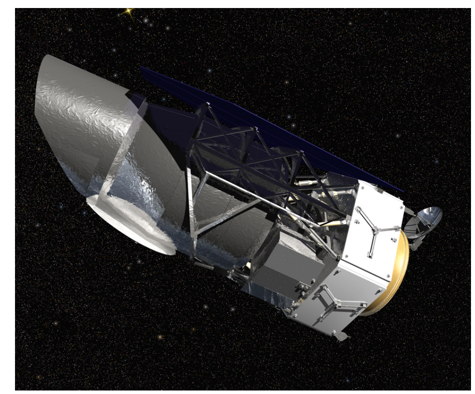
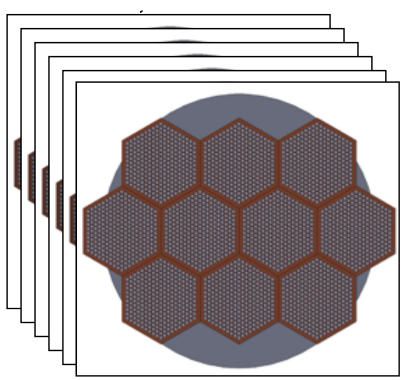
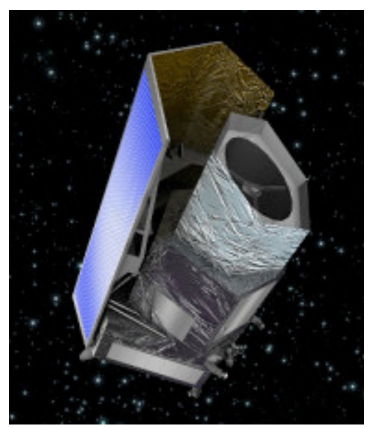


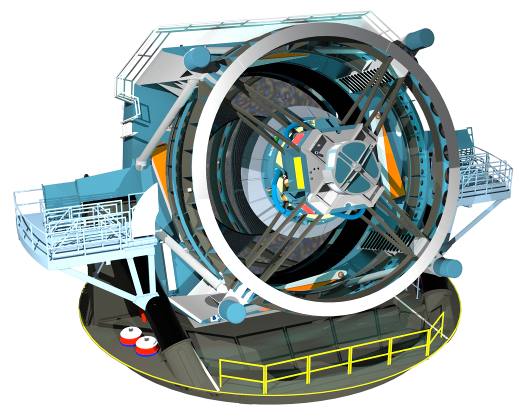
Combining Forces! Correlating surveys in the 2020s

Rachel Bean (Cornell University)
LSST DESC Spokesperson

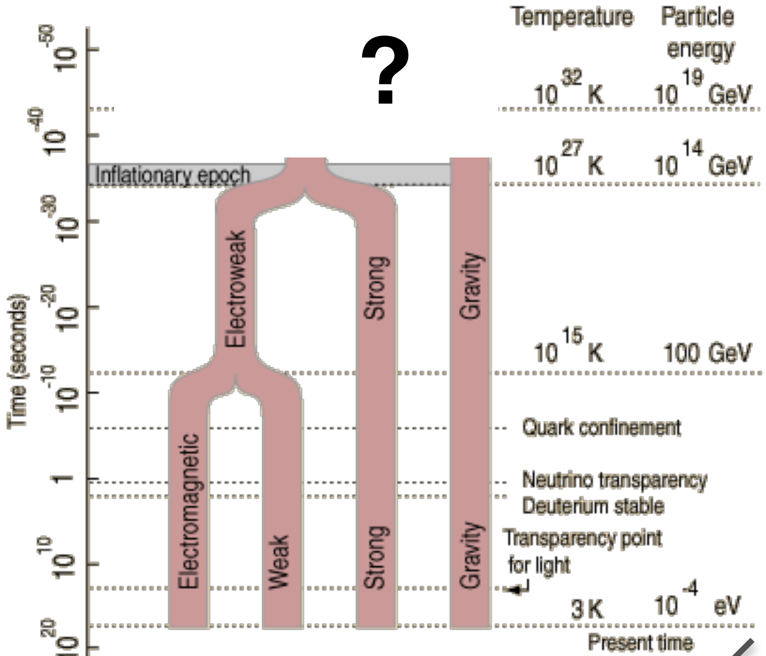








The Cosmos is a valuable physical laboratory! Probing energy and length scales inaccessible on earth

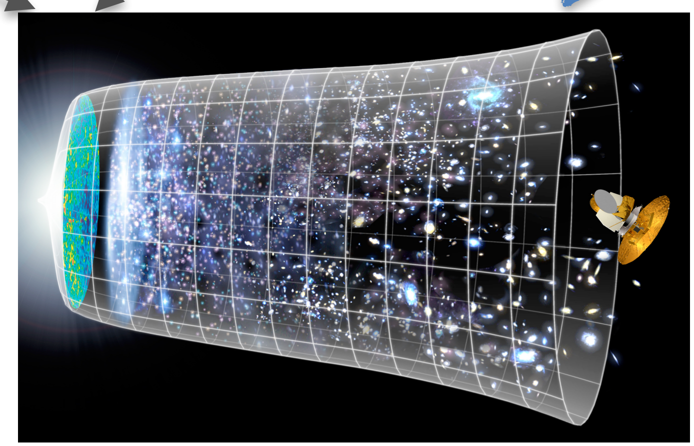


HyperPhysics (©C.R. Nave, 2010)

Inflation (accelerated expansion) t ~10^{-35}s. Density & gravitational wave fluctuations.

Cosmic neutrino background (CMB) t~1s

Cosmic Microwave Background (CMB) t~40,000 years



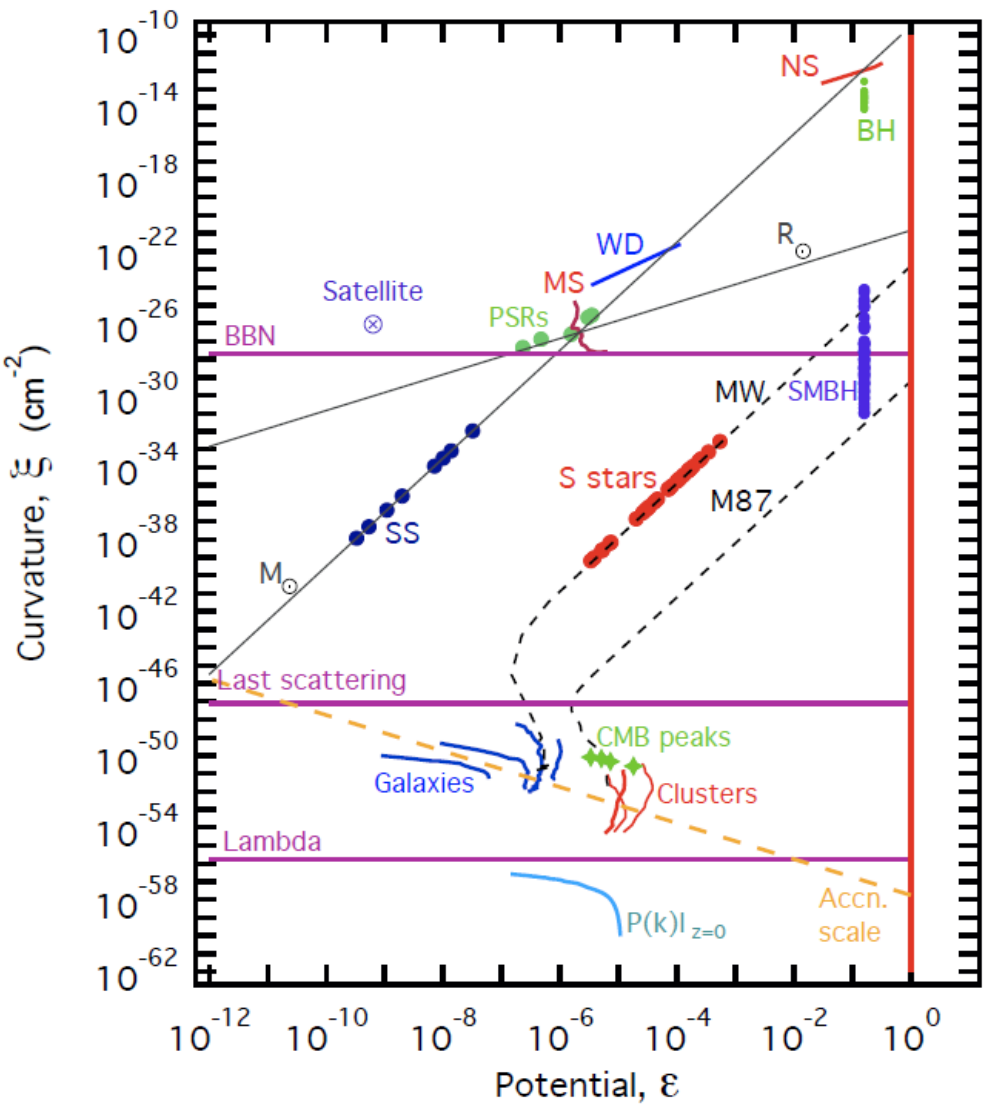
CMB traverses through LSS

Gravitational potentials traced by galaxy positions+motions and CMB secondary anisotropies

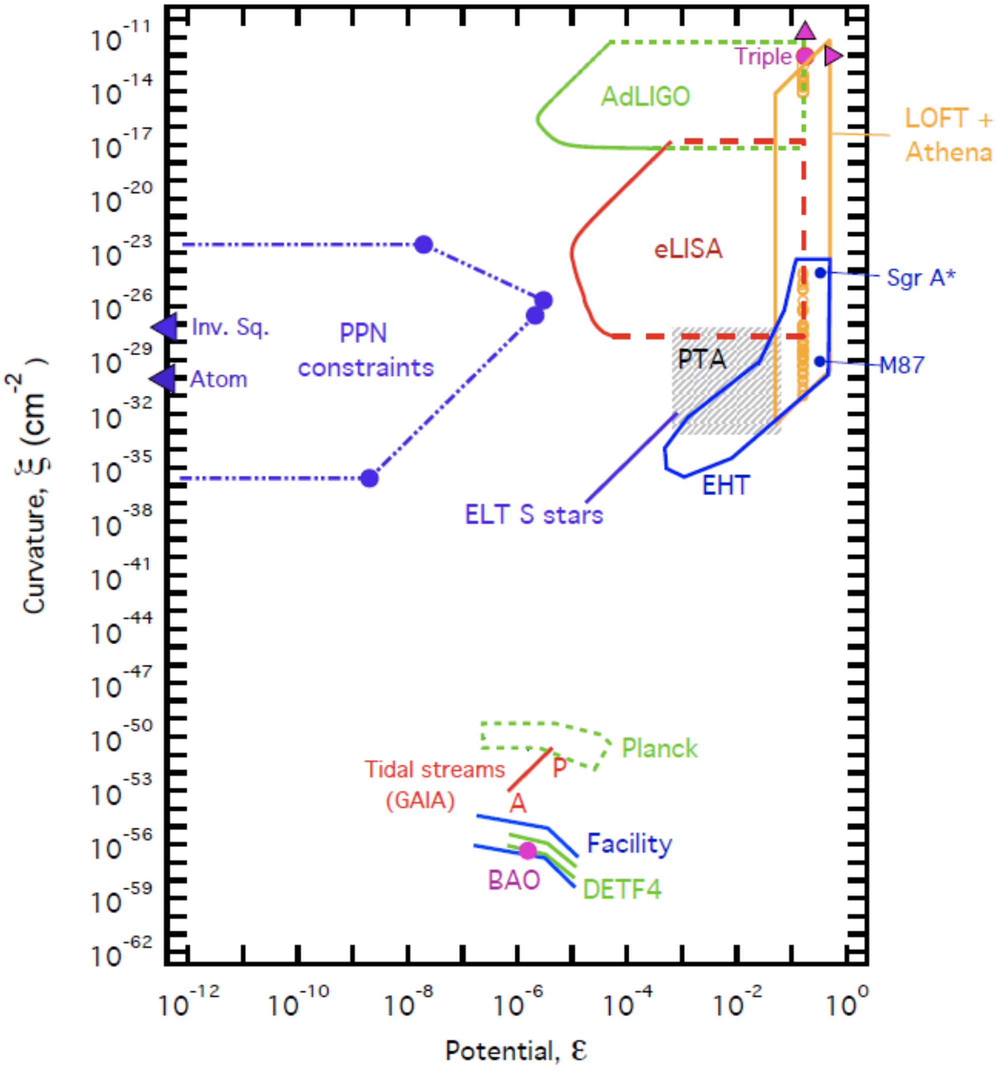
Cosmic Acceleration: New matter or gravity?

Test of gravity & matter in environments beyond stellar systems

Gravitational Field Parameter Space



Experimental Space



Credit: Baker et al ApJ 2015

Observational probes of Dark Sector & Inflationary physics

	Physical Observable	Sensitivity to Dark Sector, Gravity and Inflationary Physics
Imaging LSS Surveys	• Correlated galaxy positions and distortions in shapes • Time delays of multiply lensed sources	• Geometry & growth of structure (projected along line of sight) • Distance-redshift relation
Spectroscopic LSS Surveys	• Galaxy clustering (BAO & Redshift-Space Distortions) • Cluster numbers & masses	• Distance-redshift relation • Motions under gravity • Initial conditions from inflation
Supernovae Surveys	• Standard candle fluxes	• Distance-redshift relation
CMB Surveys	• CMB primary & secondary temperature + polarization (incl. ISW, lensing, tSZ, kSZ)	• Geometry • Initial conditions from inflation • Geometry & growth of structure (projected along line of sight)

Phenomenological modeling of gravity

- Modify Einstein's equations relating metric perturbations (Ψ,Φ) to perturbations in density Δ

$$k^2\Psi = -4\pi G_{matter} a^2 \rho\Delta \qquad k^2(\Psi+\Phi) = -8\pi G_{light} a^2\rho\Delta$$

- Connect predictions to underlying theories e.g. Horndeski theories

$$G_{mat}(a,k) = \frac{1+(1+\frac{\alpha'^2}{2})\frac{B_0}{2}\bar{k}a^s}{1+\frac{B_0}{2}\bar{k}a^s}$$

$G_{light}=1$

- While $G_{matter}/G_N \neq 1$ may be mimicked by unknown dark sector clustering

- $\Psi/\Phi \neq 1$, "Slip", not easily mimicked => smoking gun for modified gravity?

- CDM growth rate exponent, γ ~0.55 for LCDM, is an alternative parameterization, to G_{matter},

Neutrino mass and primordial inflation signatures

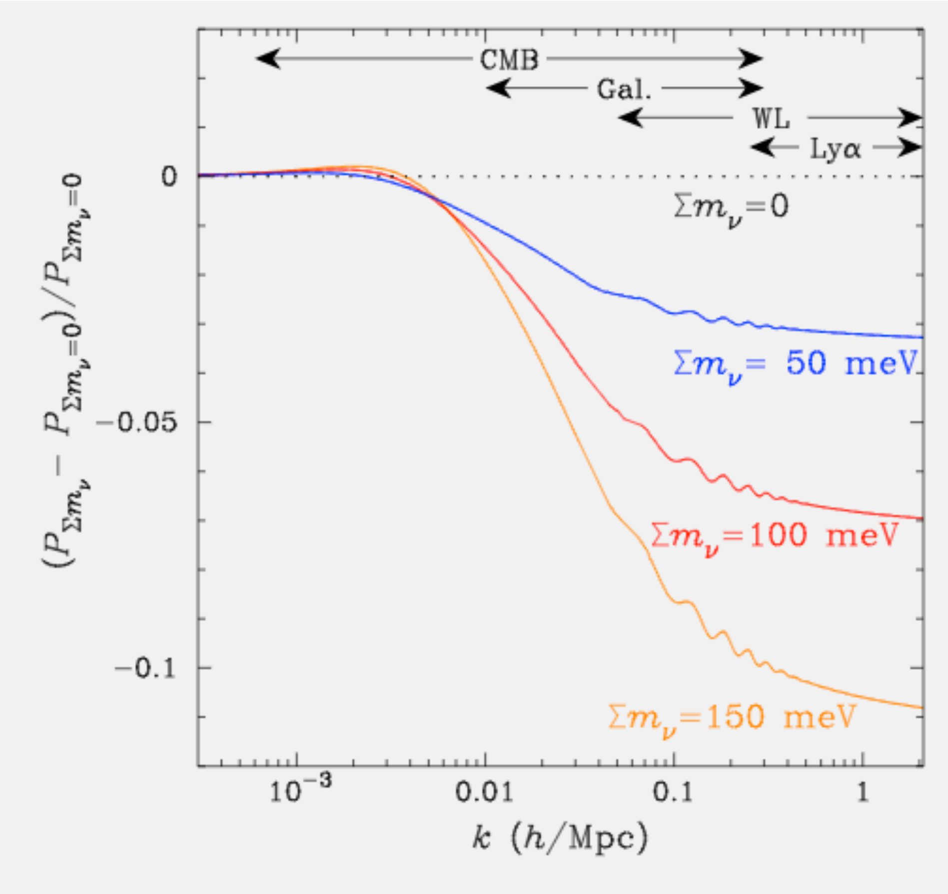
- LSS and CMB correlations constrain density power spectra across multiple scales

- Massive neutrinos introduce scale-dependent suppression of structure

- Primordial power spectrum (and bispectrum) shape and features imprinted

- Inflationary gravitational waves signature in CMB polarization

$$r \equiv \frac{\text{Tensor (gravitational) perturbation amplitude}}{\text{Scalar (density) perturbation amplitude}}$$

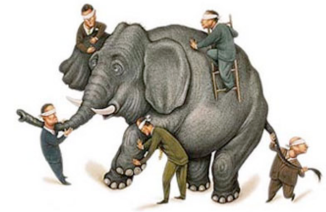


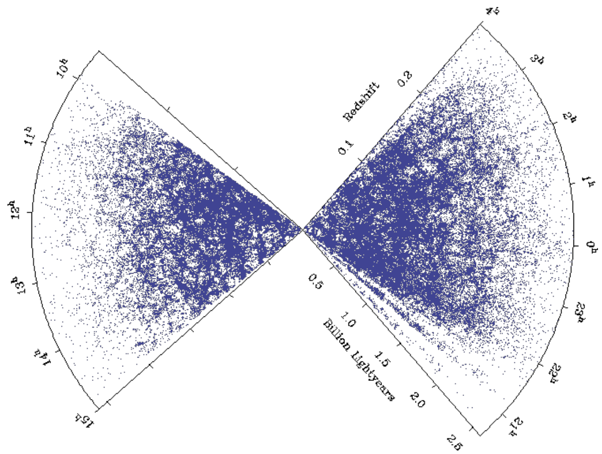
Abazajian et al 2013

$$\text{energy} = 10^{16}\left(\frac{r}{0.01}\right)^{\frac{1}{4}} \text{GeV}$$

$$\text{time} = 10^{-36}\left(\frac{r}{0.01}\right)^{-\frac{1}{2}} \text{seconds}$$

Correlations provide complementary insights into properties of gravity





Non-relativistic tracers: Galaxy and cluster positions & motions :

- Sensitive to ψ
- Measurable at specific z
- Biased tracer

Relativistic tracers: Weak lensing, CMB lensing & ISW

- Sensitive to $(\phi+\psi)$
- Projected along line of sight
- Direct tracer of potential, (but still plenty of systematics)

Contrasting both can get at "Gravitational Slip"= ϕ/ψ

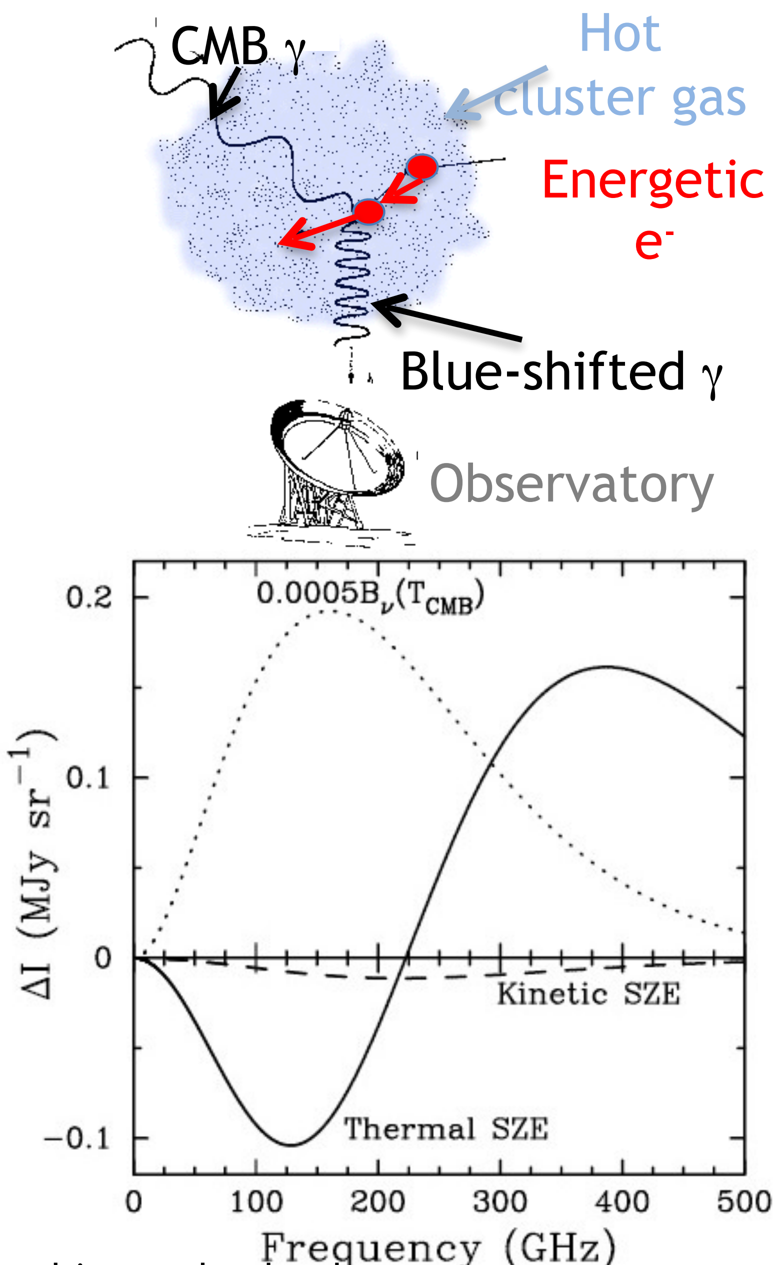
Zhang et al 2007

Correlations open up new techniques: e.g. kinetic SZ

- Cluster dynamics provide an alternative direct probe of the gravitational potential.
- Measurable via the kinetic Sunyaev Zeldovich (kSZ) effect

$$\frac{\Delta T_{kSZ}}{T_{CMB}} = -\tau\left(\frac{v_{pec}}{c}\right)$$

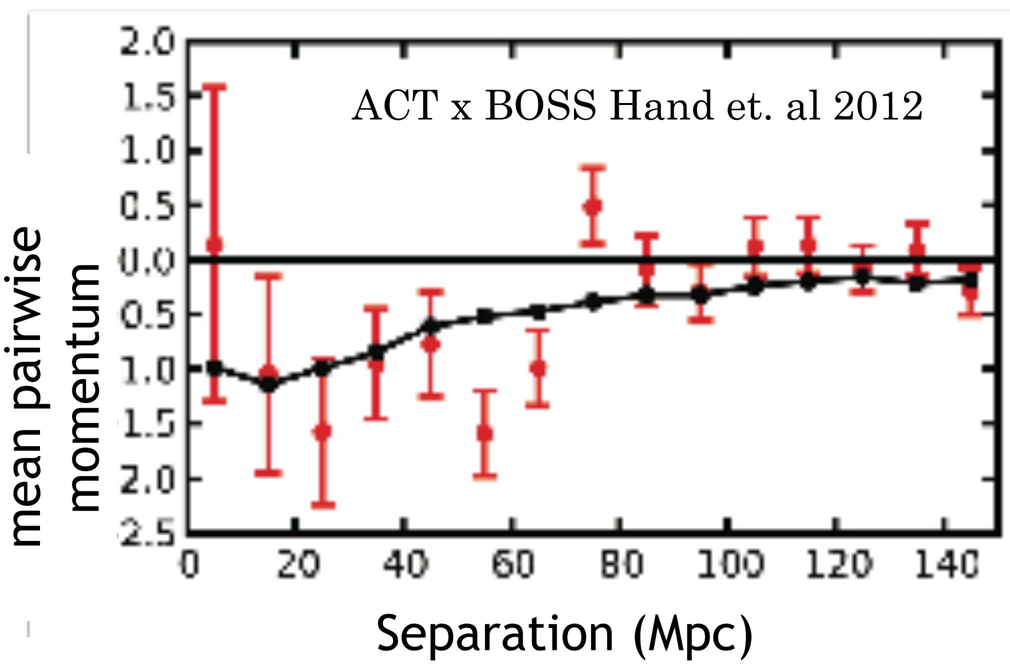
- Problem: kSZ has weak frequency dependence and small amplitude (compared to thermal SZ)

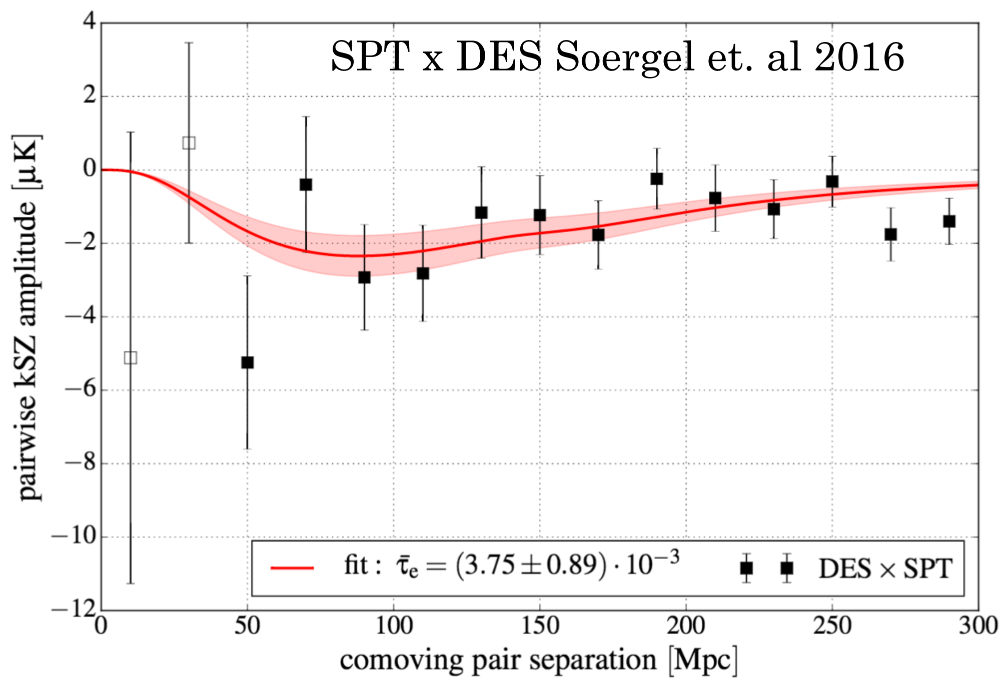


ned.ipac.caltech.edu

The kinetic SZ effect

- Solution: isolate kSZ through cross-correlation
  - Use galaxies (either LRGs or RedMaPPer) to trace cluster centers
  - Cut out a postage stamp/ filter CMB with aperture ~few arcmin,
  - Cross-correlate temperature residuals between cluster pairs

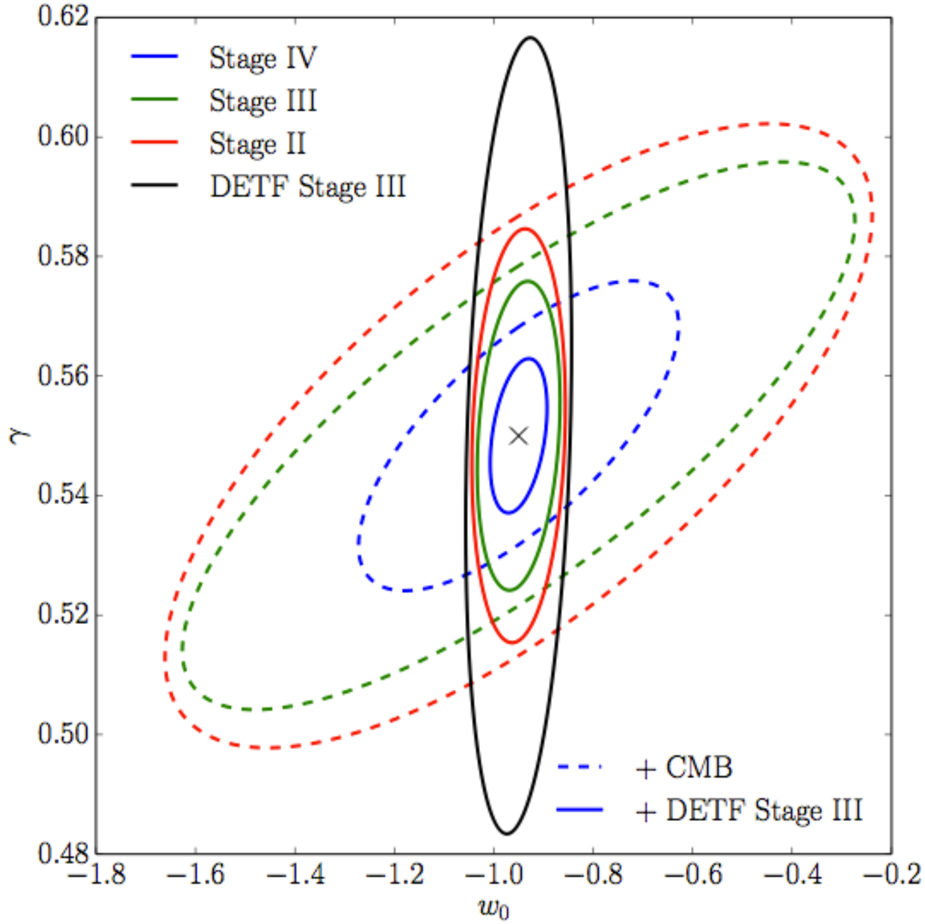


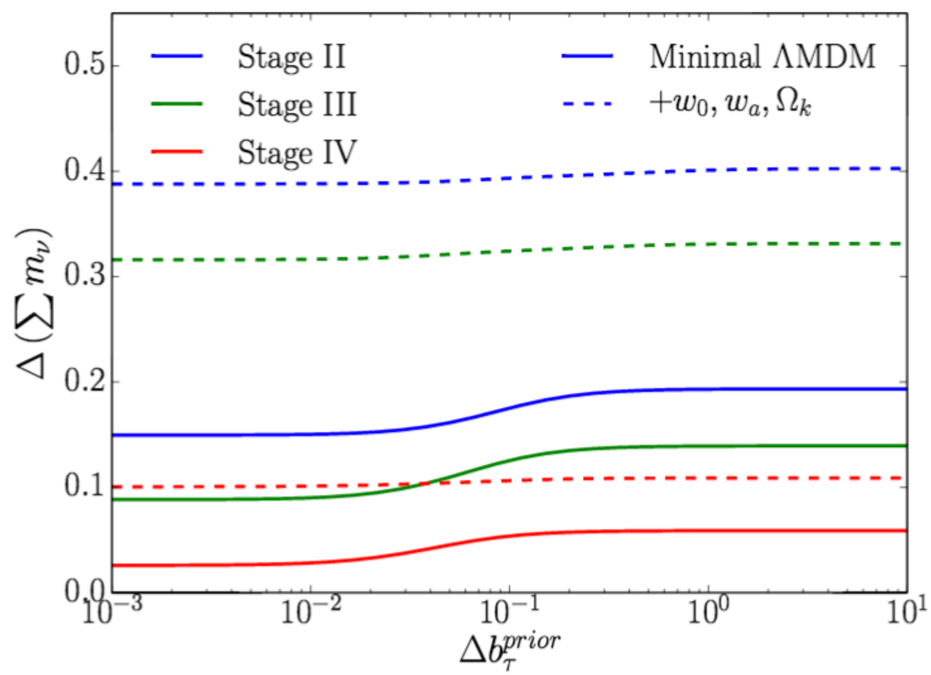


kinetic SZ: exciting potential!

- Future constraints
  - Stage III: BOSS + Adv. ACTPol
  - Stage IV: DESI + CMB-S4

		Survey Stage		
Survey	Parameters	II	III	IV
CMB	$\Delta T_{\rm instr}$ (μKarcmin)	20	7	1
Galaxy	$z_{\rm min}$	0.1	0.1	0.1
	$z_{\rm max}$	0.4	0.4	0.6
	No. of z bins, N_z	3	3	5
	$M_{\rm min}$ ($10^{14} M_\odot$)	1	1	0.6
Overlap	Area (1000 sq. deg.)	4	6	10





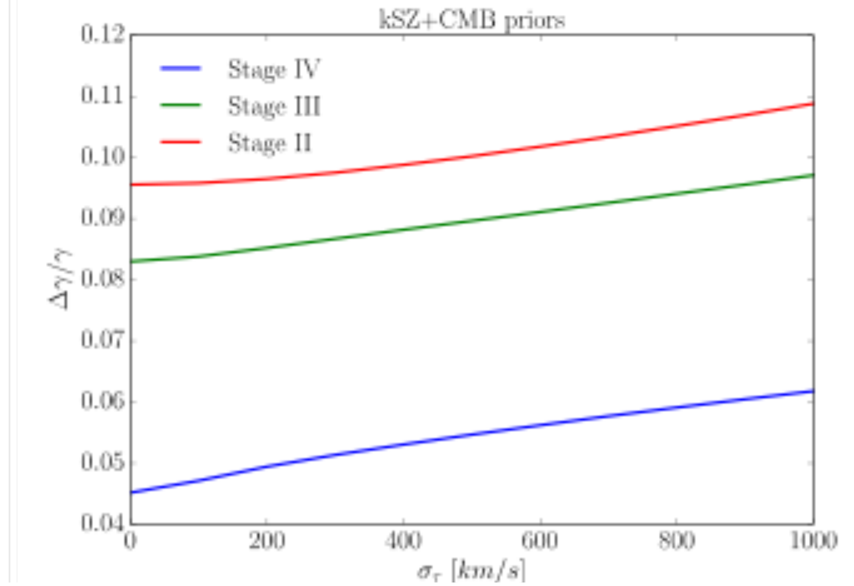
Mueller, De Bernardis, Bean, Niemack 2015

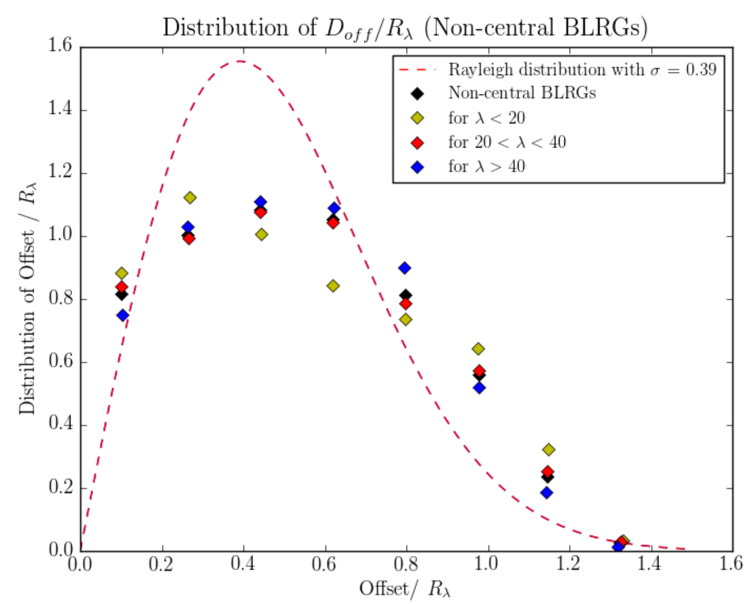
Plenty of complications: galaxy & CMB data will help

- Cluster optical depth
  - CMB polarization + thermal SZ

$$\frac{\Delta T_{\rm kSZ}}{T_{\rm CMB}} = -\frac{v}{c}\tau,$$

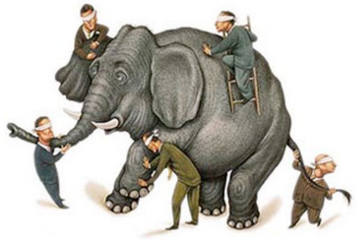
- Cluster centering
  - Photo-z galaxy samples give richer info on central galaxy
- Foreground contamination
  - Photometric surveys help isolate foreground structures
- Sub-mm galaxy emission
  - Multi-frequency sub-mm maps





Mueller, De Bernardis, Bean, Niemack 2015
In prep with Victoria Calafut + Byeonghee Yu

Diverse Surveys: Current and Future

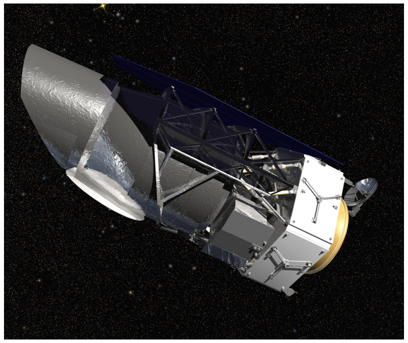


Upcoming surveys will benefit greatly from the valuable lessons learned, challenges overcome and science discoveries of current surveys.

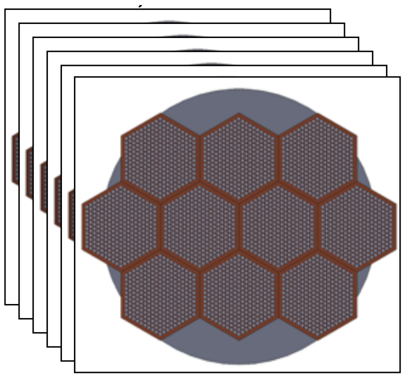
Data type	Recent/Upcoming	Future (2018-2025)
Imaging LSS/ Weak lensing	DES, HSC	LSST, Euclid, WFIRST
Spectroscopic LSS	BOSS, HETDEX, eBOSS	DESI, Euclid, PFS, WFIRST
Type 1a Supernovae	HST, Pan-STARRS 1, SCP, SDSS,SNLS, DES	JWST, LSST, WFIRST
CMB	Planck, Advanced ACTPol, SPT-3G, SPIDER	CMB S4, LITEbird
Submm, radio, lensing + SZ cluster	SKA precursors, CHIME	SKA
X-ray clusters	ROSAT, XMM, Chandra	XMM (XCS/XXL), eROSITA

Upcoming "Stage 4" Cosmological Surveys

Dark Energy Spectroscopic Instrument (DESI)
DOE-led, Kitt Peak AZ, 2018

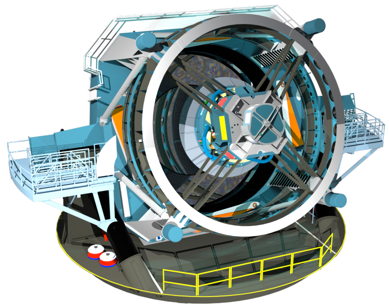


Euclid
ESA-led + NASA
L2, launch late 2020

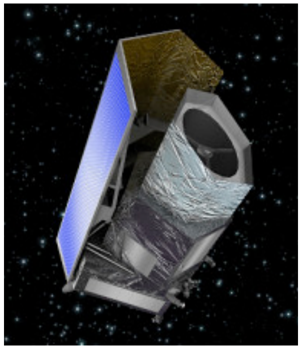


CMB-S4
Ground-based:
Chile or South Pole?
early 2020s?
DOE and NSF roles

Complementary NASA balloon mission?



Large Synoptic Survey Telescope (LSST)
Cerro Pachon, Chile, 2019
(survey 2021), NSF+DOE-led



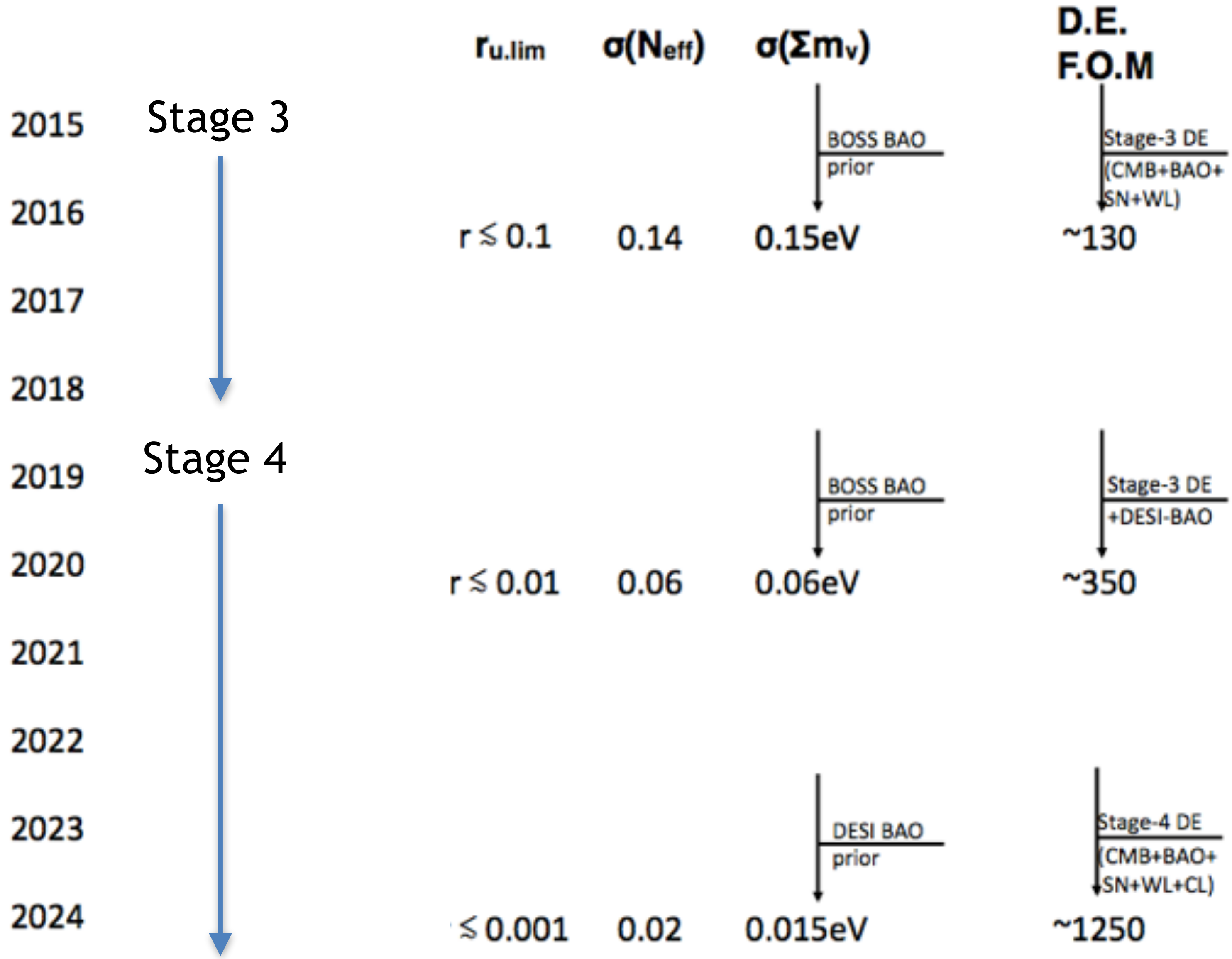
WFIRST
NASA-led
L2, launch 2024

Upcoming Surveys: Different strengths & systematics

(based on publicly available data)

Stage IV	DESI	LSST	Euclid	WFIRST
Starts, duration	~2018, 5 yr	2020, 10yr	2020 Q2, 6.25yr	~2025, 5-6 yr
Area (deg^2)	14,000 (N)	20,000 (S)	15,000 (N + S)	2,400 (S)
FoV (deg^2)	7.9	10	0.53	0.281
Diameter (m)	4 (less 1.8+)	6.7	1.3	2.4
Spectroscopic	Y (fibers)		Y (grism)	Y (grism)
	LRGs+ELGs z~0.6-1.7 (20-30m), QSOs/Lya 1.9<z<4 (1m)		ELGs: z~0.7-2.1 (~20m)	ELGs: z =1-2 (20m), 2–3 (2m)
Photometric		Y	Y	Y
Galaxies (per sq arcmin)		~30 over 6 bands (ugrizy)	~30-35, in one broad optical + IR band	68, in 3 bands into near IR
SN1a		10^4-10^5 SN1a/yr z = 0.–0.7 photometric		2700 SN1a z = 0.1–1.7 IFU spectroscopy

Rich cosmological discovery potential



Credit: John Carlstrom (CMB-S4)

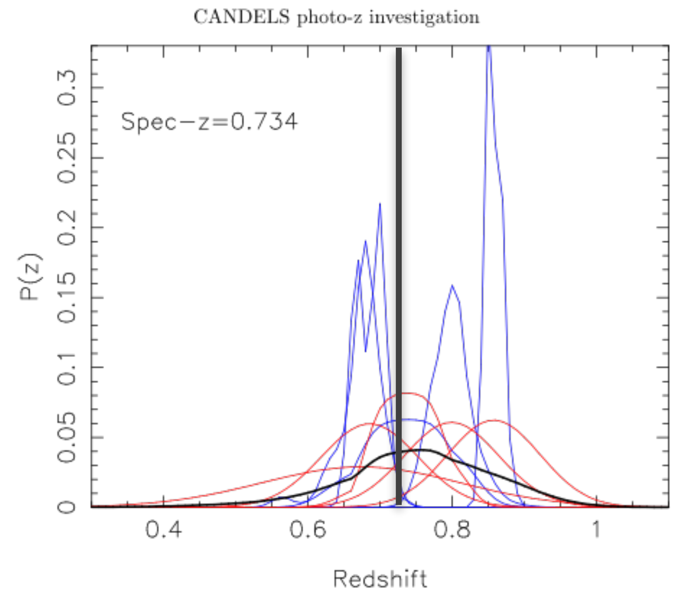
A single survey can't give the full picture

- Trade offs/complementarity in
  - Probes
  - Photometric speed vs. spectroscopic precision
  - Survey area vs depth
  - Astrophysical tracers (LRGs, ELGs, Lya/QSOs, clusters)
  - Epochs, scales and environs being studied

- Rich cross-correlation/joint analysis
  - To leverage additional complementary science, e.g.
    - gravitational slip
    - Kinetic Sunyaev Zeldovich effect
  - To mitigate pernicious systematic uncertainties, e.g.
    - Atmospheric contamination
    - Chromatic PSF effect
    - Photometric redshift errors, intrinsic alignments, galaxy magnification, magnification biases etc…

Correlations: Photometric redshifts

- Photometric surveys quicker (more galaxies) and concurrent with imaging, but less accurate than spectral z

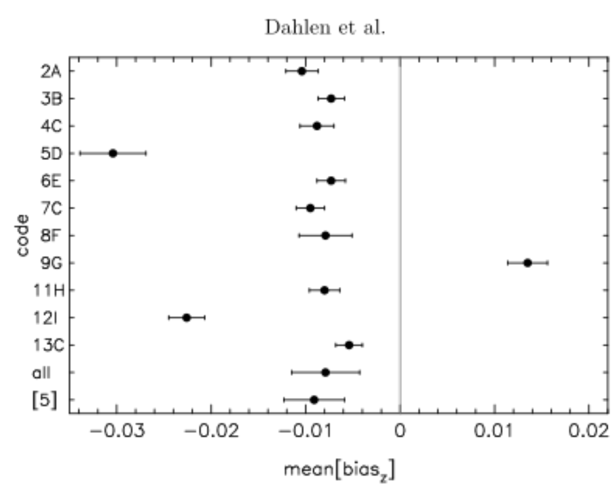


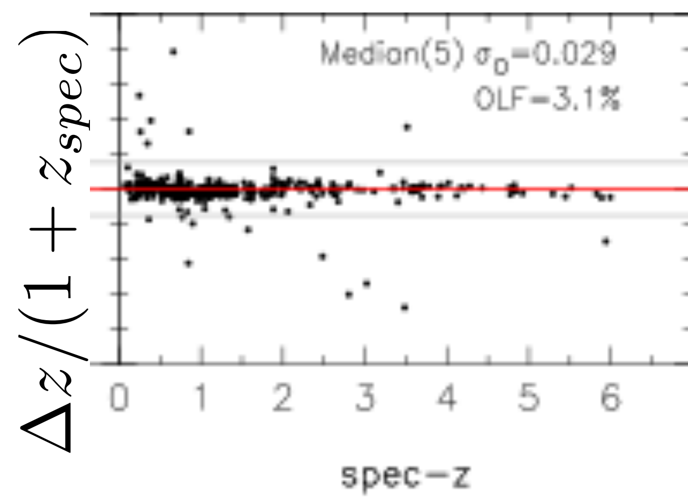
- Challenge: refine photo-z estimates given disparate & incomplete spectroscopic samples
    - z probability distribution dispersed and biased relative to the spectroscopic z.

- Spectroscopic datasets crucial

$$\sigma_z = rms\left[\frac{\Delta z}{1+z_{spec}}\right]$$

$$bias_z = mean\left[\frac{\Delta z}{1+z_{spec}}\right]$$





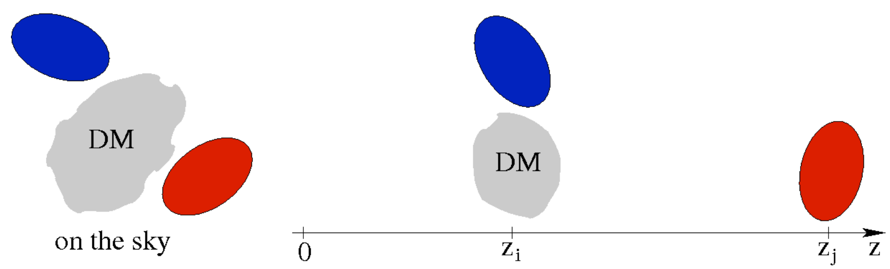
Dahlen et al 1308.5353

Correlations: Intrinsic alignments

- Galaxy Intrinsic shapes are aligned in their host halo

$$\epsilon^{(i)}(\theta) = \gamma_G^{(i)}(\theta) + \gamma_I^{(i)}(\theta) + \epsilon_{\rm rnd}^{(i)}(\theta)$$

- Observed shape correlations include both lensed and intrinsic terms



$$C_{\epsilon_i\epsilon_j} = C_{G_iG_j} + C_{G_iI_j} + C_{I_iG_j} + C_{I_iI_j}$$
$$C_{n_i\epsilon_j} = C_{g_iG_j} + C_{g_iI_j}$$

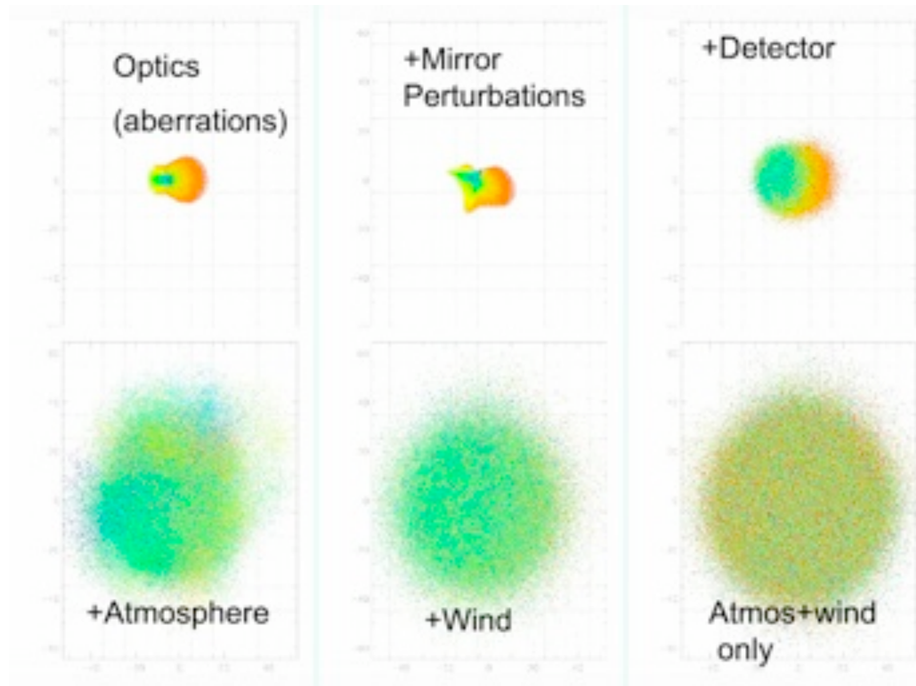
- IA amplitude a function galaxy type, luminosity and redshift
- Correlation with CMB lensing, CMB not contaminated by IA…

Correlations: Shear contamination

- Incomplete correction of the atmospheric and instrumental PSF can induce additive and multiplicative shear errors

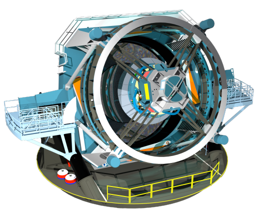
$$\epsilon_i = (1 + m_i)\epsilon_i + a$$

- Correlations with CMB lensing can be used to calibrate biases

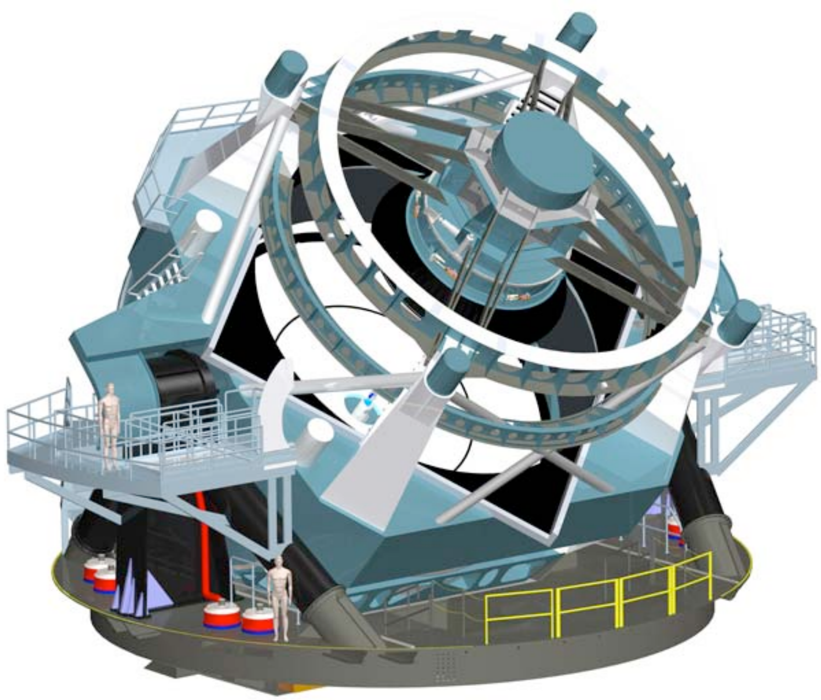


LSST Project

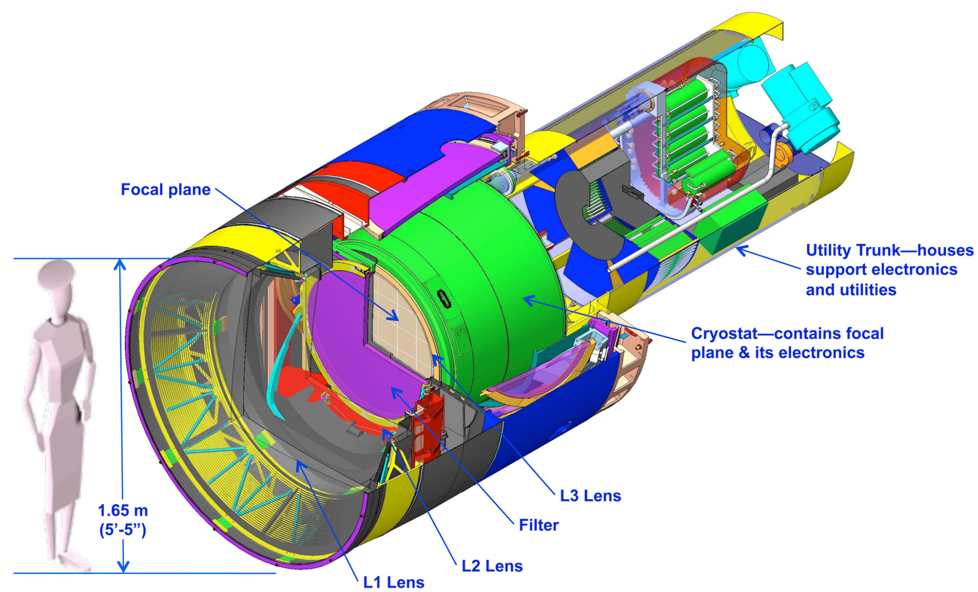
LSST Camera and Telescope



- 8-meter class telescope sited in Chile



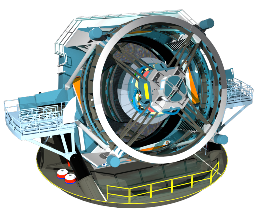
- April 2015: Ground breaking
- Jan 2016: Drone image from
- Late 2017: Summit facility and dome to be completed



Camera ¾ Section

- 3.2 Gpix camera with 2 sec. readout
- 21 "rafts" each containing 3x3 CCDs
- 9.6 sq. deg. field of view
- 0.2 arcsecond resolution
- 6 filters (ugrizy)

LSST in summary



- A 10 year, deep multi-band & fast time-domain optical survey

- 4 broad science themes set complementary system design requirements
  - Taking a census of moving objects in the solar system.
  - Mapping the structure and evolution of the Milky Way.
  - Exploring the transient optical sky.
  - Determining the nature of dark sector. ("Stage IV" survey)

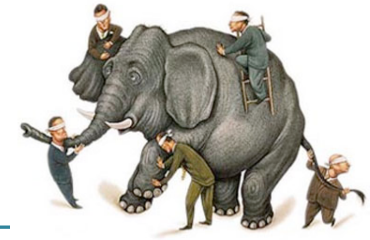
- LSST Data Management: unprecedented data volumes and richness
  - 15 TB (and millions of objects) per day, 100 PB survey data in total
  - Nightly alerts (Level 1) & annual image catalogs (Level 2)
  - For cosmological science: 18,000 sq. deg., 4 billion galaxy and 100,000 supernovae images

- Science analysis left to LSST community
  - LSST Dark Energy Science Collaboration (DESC) is one community effort.

LSST Dark Energy Science Collaboration (DESC)

- Data volumes and complexity leading to changes in scientific approach
  - Larger collaborations modeled on HEP style structure
  - Members with astrophysics and particle physics backgrounds
- DESC: Bringing together scientists to prepare for and carry out cosmological analyses with LSST data
  - DOE is the lead agency
  - Democratic, member-based governance
  - 12 working groups span expertise in instrumentation, computing, observing & theory
  - Rapidly evolved since inception in 2012: >490 members, 156 "full members" over 4 continents
- Lots of work to be ready for LSST commissioning. Join us!
  - Info @ public website: http://www.lsst-desc.org/
  - Near term tasks: DESC Science Roadmap

To conclude

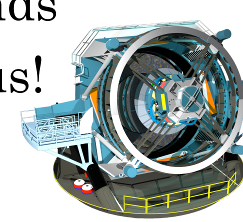


- DESI, LSST, Euclid & CMB-S4 +: unprecedented potential for insights into:
  - the properties of gravity and dark energy on cosmic scales
  - the sum of the neutrino masses
  - the theory of inflation

- Varied probes critical to provide rich insights into cosmology
  - complementary tracers and epochs
  - different sensitivity to the facets of fundamental physics and distinct systematics (e.g. gravitational slip, lensing calibration, IAs)
  - their combination opens up new signals/detections (e.g. kSZ)

- "New era" 1-2 order of magnitude increases in data volumes, complexity and potential
  - Lots of work to do now, prior to commissioning, to be ready at first light
  - Concerted, collaborative efforts of researchers from diverse backgrounds
  - We welcome interested members of the HEP community, please join us!

LSST DESC Dark Energy Science Collaboration



Back up slides

Specific MG example: Horndeski theories

- Examples include f(R), Chameleon and symmetron theories
- Einstein frame action is a non-minimally coupled scalar field

$$S_E = \int d^4x \sqrt{-\bar{g}} \left[\frac{M_P^2}{2} \bar{R} - \frac{1}{2} \bar{g}^{\mu\nu} (\bar{\nabla}_\mu \phi) \bar{\nabla}_\nu \phi - V(\phi) \right] + S_i \left(\chi_i, e^{-\kappa\alpha_i(\phi)} \bar{g}_{\mu\nu} \right) .$$

- Leads to modified Poisson equation, G_{mat}

$$G_{mat}(a,k) \quad = \quad \frac{1 + (1 + \frac{\alpha'^2}{2}) \frac{B_0}{2} \bar{k} a^s}{1 + \frac{B_0}{2} \bar{k} a^s}$$

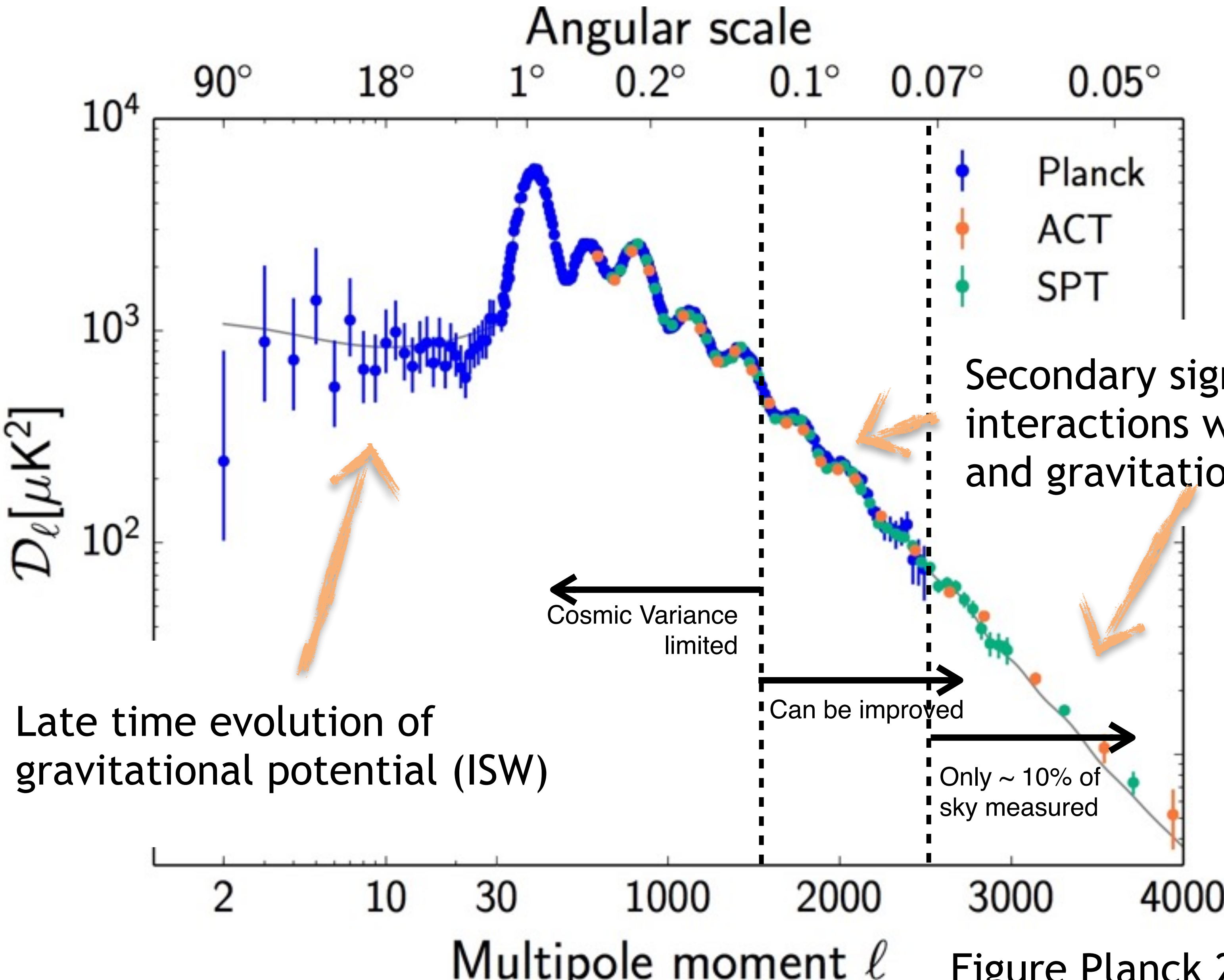
$$\bar{k} = \frac{ck}{H_0}$$

$$\frac{B_0}{2} = \left(\frac{H_0}{m_0 c} \right)^2$$

$$am = m_0 a^{-s/2}$$

  - f(R): $\alpha'^2 = 2/3$, $B_0 < 5\times10^{-5}$ ($1/m_0 >\sim 20$Mpc)
  - Chameleon: $\alpha'^2 \sim O(1)$, $B_0 \sim [0,1]$

CMB temperature: ISW, lensing and cluster physics



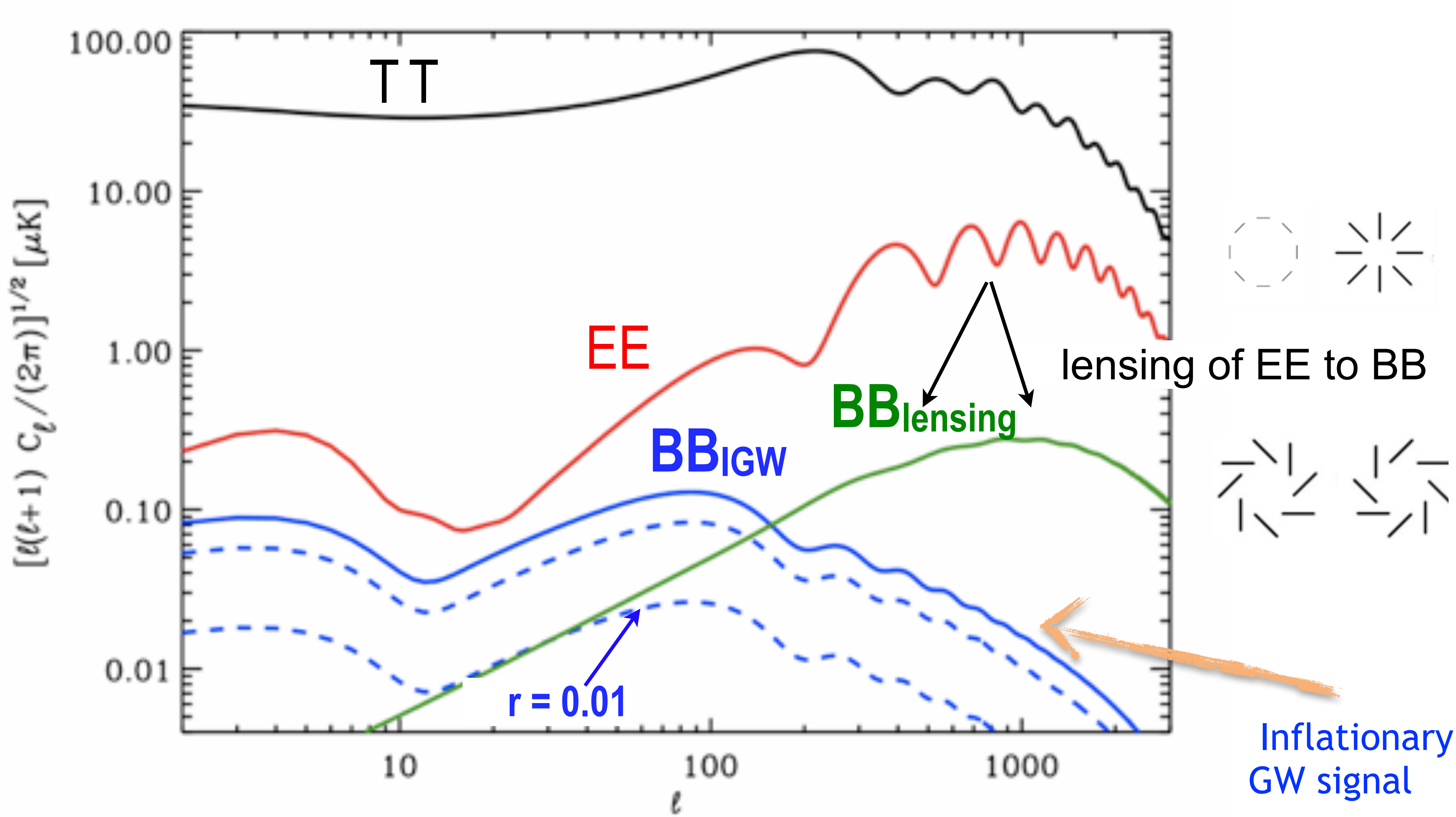
Secondary signals from interactions with clusters and gravitational lensing

Late time evolution of gravitational potential (ISW)

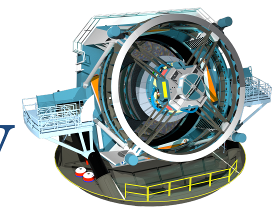
Figure Planck 2015 XI + J. Carlstrom comments

CMB polarization: lensing and inflationary GW

- The challenge: achieve sensitivity (10nK), de-lens and remove galactic foregrounds to reveal inflationary GW signature in B-mode polarization

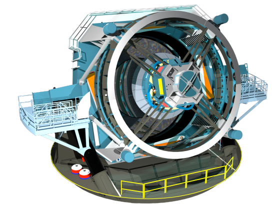


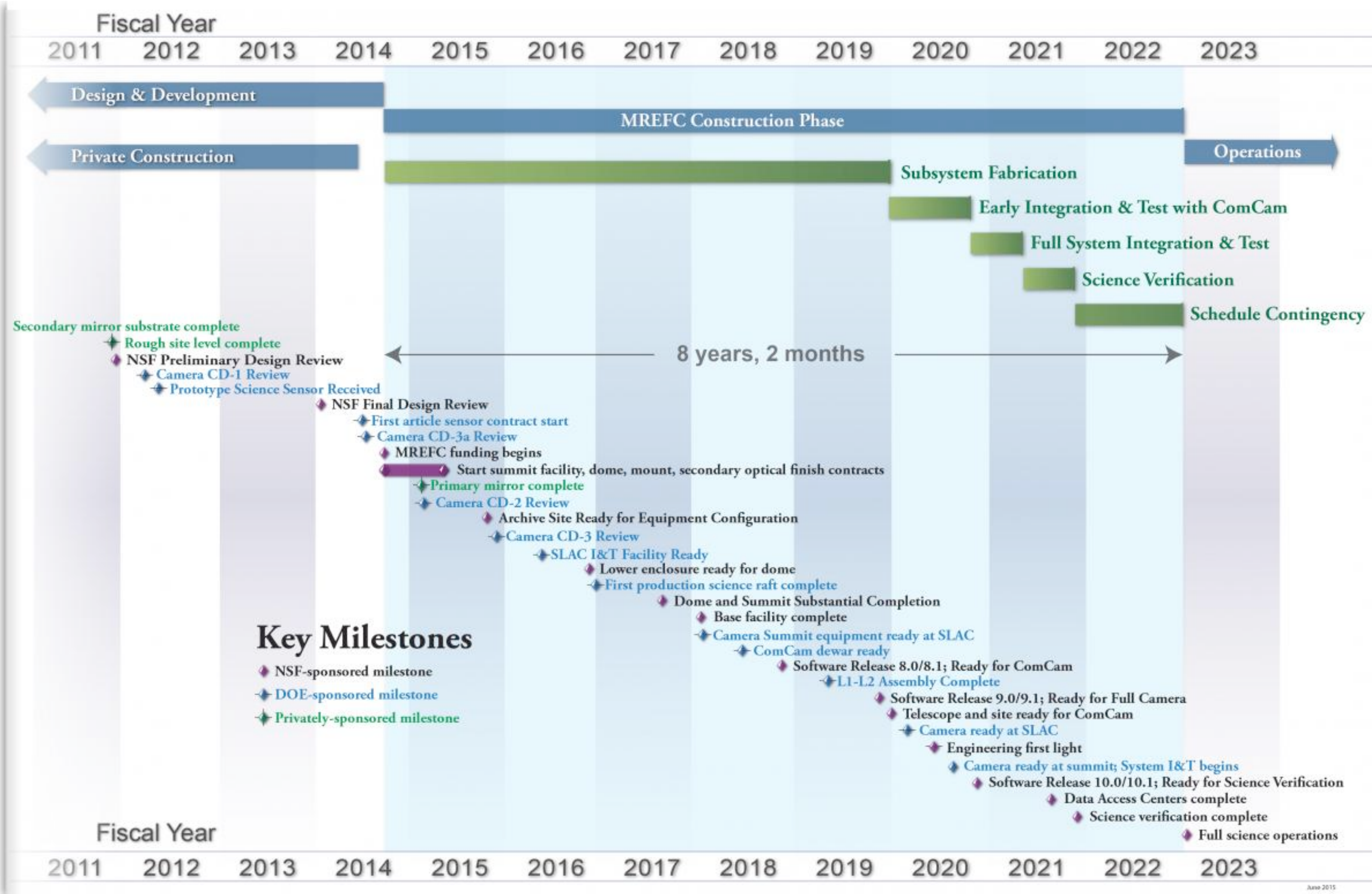
Broad collaboration on LSST Camera Delivery



- SLAC National Accelerator Laboratory
  - Overall project management, camera body and mechanisms, cryostat subsystems, data acquisition and electronics, camera controls, integration and testing
- Brookhaven National Laboratory
  - Science sensors, electronics and raft assembly
- Lawrence Livermore National Laboratory
  - Project management, optics, corner rafts and wavefront sensors
- Institut National de Physique Nucleaire et de Physique des Particules (IN2P3-Collection of multiple labs):
  - Front-end electronics, sensors, sensor testing, filters, filter carousel, camera calibration, slow controls
- University-based instrumentation groups:
  - Harvard University, U. of Pennsylvania, Purdue University, Ohio State, U. of Illinois, UC Santa Cruz, U. of Arizona, UC Davis

LSST Timeline





LSST Key Numbers

Survey Property	Performance
Main Survey Area	18000 sq. deg.
Total visits per sky patch	825
Filter set	6 filters (ugrizy) from 320 to 1050nm
Single visit	2 x 15 second exposures
Single Visit Limiting Magnitude	u = 23.5; g = 24.8; r = 24.4; I = 23.9; z = 23.3; y = 22.1
Photometric calibration	2% absolute, 0.5% repeatability & colors
Median delivered image quality	~ 0.7 arcsec. FWHM
Transient processing latency	60 sec after last visit exposure
Data release	Full reprocessing of survey data annually

http://www.lsst.org/scientists/keynumbers